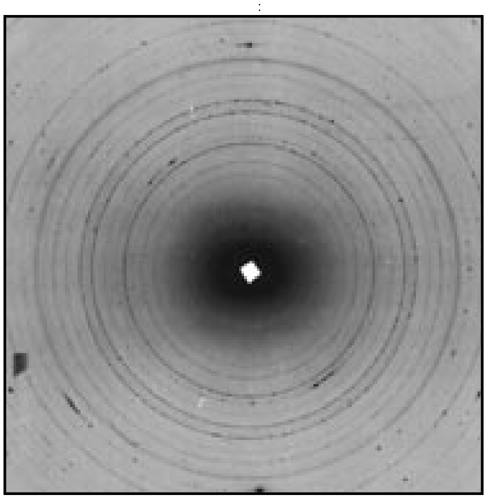
Physics and Space Technology

In 1994 we made important progress in many areas, including condensed matter physics, plasma processing, nuclear science and technology, atomic physics, and space science and technology.

Physics at the Laboratory originated as a pursuit of long-term research in the behavior of nuclear explosives. Space technology at the Laboratory originated in research and development for the Strategic Defense Initiative. Today, Physics and Space Technology encompasses a range of activities, from fundamental research to advanced technology development, that are relevant to the broadened mission of the Laboratory. Included are the maintenance of a safe, reliable U.S. stockpile; enhanced efforts in nonproliferation, treaty verification, and counterterrorism; the design of inertial confinement fusion experiments leading to the National Ignition Facility; and contributions to U.S. industrial competitiveness. Some areas of current emphasis are summarized below.

The angle-resolved diffraction pattern of laser-heated silicon in nitrogen at 1400 K and 2 GPa, showing a formation of b-Si_3N_4. The b-Si_3N_4 can be recovered at ambient condition. The diffraction pattern was obtained using an image plate detector and monochromatic x rays at the Stanford Synchrotron Radiation Laboratory.



Physics of Materials

There is increasing interest in the creation of materials with novel properties, including enhanced energetic content, superhardness, and useful electronic or optical characteristics. We are engaged in designing such materials using supercomputers and synthesizing them under high pressure and temperature. We work at the atomic level to optimize the properties of these materials for specific applications. A combined theoretical and experimental effort in shock and high-pressure physics has determined the equation of state of materials under unusual conditions.

Optical Properties of Lead Fluoride

The need to efficiently detect gamma and x rays in medicine, health and safety, and nonproliferation has motivated a search for new scintillator materials with improved radiation-detection capabilities. Lead fluoride (PbF_2) may be such a material. We are studying its dynamical and electronic properties. We have experimentally verified that PbF_2 transforms into an alternative phase with increasing pressure, and we have recovered it as a stable compound at ambient conditions. Our theoretical work suggests that structural imperfections are responsible for the observed scintillation in this phase of PbF_2.

Temperature of Shock-Compressed Hydrogen

We measured the temperature of shock-compressed liquid hydrogen and deuterium for the first time. Our results may significantly affect target designs for inertial confinement fusion. While the temperatures of singly shocked H_2 and D_2 agree well with previous models up to pressures of about 20 GPa, reshocking these fluids at pressures up to 85 GPa and temperatures of over 5200 K produces shock temperatures that are significantly lower than predicted. The molecules absorb energy to break the bonds between the atoms; the absorption of energy reduces the temperature. Our new theoretical model correctly accounts for the dissociation of molecular hydrogen and deuterium at these extreme conditions.

Laser Heating Materials at High Pressures

We have applied x-ray diffraction techniques to materials laser-heated at high pressures in a diamond-anvil apparatus to study their structure at pressures and temperatures far beyond the reach of other technology. For example, we discovered a new phase of iron at 2000 K and 40 GPa, and we demonstrated the metastability of the existing iron phase. These results imply that the iron phase diagram needs major modification and provide a crucial constraint for models of the Earth's core. We have also applied the technique to synthesizing superhard materials and metastable energetic phases. We have found the direct reactions of nitrogen with the light elements beryllium, carbon, and silicon. Some of these reactions yield technologically important nitride ceramics; others are very energetic.

Plasma Processing

LLNL's plasma processing program has two major goals: to discover and demonstrate the role of ionized gases in the destruction of hazardous gases and to develop new methods of using plasmas in materials processing, with particular emphasis on dry etching of semiconductors.

Diesel Engine Exhaust

We have collaborated with the Cummins Engine Company to demonstrate that nonthermal plasmas, by producing radicals that react with unwanted molecules, can reduce the nitric oxide in diesel engine exhaust. Since no after-treatment systems are currently available and tuning engines for low nitric-oxide emissions penalizes fuel efficiency, a commercially viable plasma cleaner would significantly improve diesel engine technology. Research is under way to reduce the energy requirements of the plasma cleaner and to produce acceptable byproducts. Working in collaboration with the Pacific Northwest Laboratory, we have shown that similar techniques can destroy volatile organic compounds, such as chlorinated hydrocarbons, and we have compared the relative efficiency of several plasma devices.

Large-Area Plasma Processing Reactor

The performance of semiconductor devices has been rapidly improved by simultaneously shrinking the individual features in silicon chips and increasing wafer size. Replacing wet etching techniques with plasma reactors has improved process control while reducing the use of toxic chemicals. We have been working with AT&T, IBM, and Sematech to develop processes using high-density reactors, based upon U.S. technology, to compete with the electron-cyclotron resonance machines marketed by the Japanese. We have constructed a large-area (75-cm-diameter) radio-frequency inductive reactor that permits a fourfold increase in processed wafer area and also accommodates flat panel substrates up to 62 cm in diagonal dimension. The U.S. Display Consortium has asked us, in collaboration with Lam Research Corporation, Xerox, and the University of Wisconsin, to develop and demonstrate plasma-etching techniques for manufacturing even larger screens.

Highlights for 1994

- Observed at the MACHO Observatory an unexpectedly large number of gravitational microlensing events of stars, a finding that is generating new theories about the inner structure of the Milky Way.
- Obtained over 1.5 million images, at high resolution, of the lunar surface using LLNL-built lightweight imaging sensors on the Clementine satellite, the first U.S. spacecraft to the Moon in more than two decades.
- Measured for the first time the temperature of shock-compressed liquid hydrogen, producing results that require improved models of the interior of the planet Jupiter.
- Developed a new technique, which combines x-ray diffraction imaging with laser heating of materials under high pressure, and used it to discover a new phase of iron and to synthesize novel materials.
- Calculated the electronic properties of a specific class of mutagens to determine their mode of binding to DNA and the origin of observed differences in mutagenic potency.
- Worked with an industrial partner to demonstrate a nonthermal plasma technique for reducing nitric oxide emission in diesel engine exhaust.
- Continued to design and fabricate critical components for the PEP-II high-energy accelerator of the B Factory.
- Developed a new computer code that combines computed-tomographic images of the human body with Monte Carlo radiation transport and evaluated nuclear data bases to accurately calculate dose distribution for radiation therapy.
- Built and tested a new atomic particle trap to confine very cold, highly charged ions to observe novel forms of nonneutral plasma.
- Flew for the first time an instrument package containing a high-resolution gamma-ray imager and a prototype 10-μm infrared remote sensor on a high-altitude balloon.
- Flight-tested the ASTRID rocket to demonstrate how a new pumped-propulsion technology would perform in atmospheric flight.

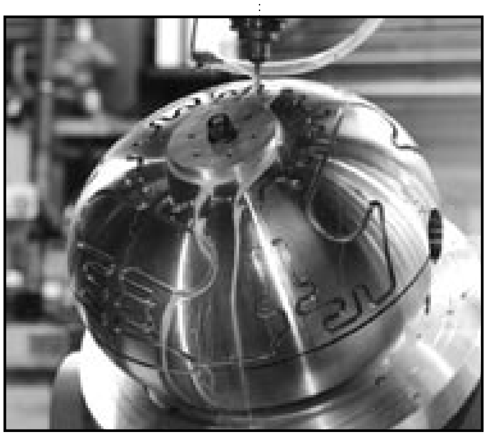
Nuclear Science and Technology

The Laboratory's strengths in nuclear science and technology make it a welcome partner in major projects in both elementary particle physics and nuclear physics. We are also exploiting our nuclear and atomic data bases and computational expertise to improve radiation treatment plans for cancer patients.

The B Factory

Recently President Clinton announced the awarding of a $300 million project to a partnership of the Stanford Linear Accelerator Center (SLAC), LLNL, and the Lawrence Berkeley Laboratory to construct and operate a high-luminosity asymmetric energy electron–positron colliding beam accelerator and detector. The facility, the B Factory, sited in a tunnel at SLAC, will produce copious pairs of b-quarks and their antiparticles so that we may study their decay in time. We want to determine why a fundamental symmetry in nature, called the charge parity symmetry, is violated in nature. The violation of this symmetry is one of three essential conditions for explaining why the universe evolved from the Big Bang with a predominance of matter over antimatter.

The B Factory project consists of the PEP-II accelerator and a detector, called BaBar, to study the decay products from the quark–antiquark pairs coming from electron–positron collisions. LLNL will design and build part or all of several systems in the accelerator. In virtually every system, the very high beam currents push the design and performance specifications to the extreme. An example is the 34 high-power RF cavities. LLNL has led a laboratory–industry consortium to develop the manufacturing process for these cavities, which involves precision deep electron-beam welding of complex shapes and diamond turning of the interior cavity surface, in order to handle the 150-kW power per cavity.



Cooling channels are being milled into the first high-power 476-MHz cavity for the PEP-II accelerator, in a numerically controlled five-axis machine in the Building 321 shop.

The BaBar detector must measure the spatial separation of the decay vertices of the b-quark and its antiquark—only a few hundred micrometers—as well as identify the type, momentum, and energy of all their decay products. LLNL designers have made innovative and important contributions to the detector. For example, we performed precision processing of the crystals for the 11,000-element cesium iodide detector array for measuring electrons and photons at high resolution.

RHIC and the Alternating Gradient Synchrotron

We are studying nuclei at extreme densities and temperatures to find both new phenomena and a primordial state of matter. The experiments are performed at the Brookhaven National Laboratory (BNL) accelerator complex, where the Alternating Gradient Synchrotron currently delivers beams of gold ions at 11.7 GeV per nucleon. BNL will soon begin to inject those beams into the new Relativistic Heavy Ion Collider (RHIC), where two beams will be accelerated to 200 GeV per nucleon and counter-circulated for colliding beam experiments.

As a result of experiments in which nuclear matter densities have exceeded five times that of normal nuclear matter, we have a better understanding of the production mechanisms and the distribution of reaction products as a function of collision orientation, and we have gained insight into the density, dimensions, and fundamental physics of the nuclear fireball.

The RHIC program will employ two large detectors, PHENIX and STAR. LLNL is the lead institution for designing and fabricating the PHENIX magnet system and is the principal U.S. coordinator for constructing the central tracking chambers. The goal of the PHENIX experiment is to look for evidence of the quark-gluon plasma—a primordial state of matter that last existed a few microseconds after the Big Bang—by measuring the photons, hadrons, electrons, and muons produced in gold–gold collisions in the RHIC.

The PEREGRINE Project

Ideally, radiation therapy delivers a lethal dose to a tumor while minimizing dose levels to nearby sensitive organs. Thus, distributing a dose requires careful calculation to avoid unnecessary damage. Current computational methods use interpolated data from dose measurements made in water, and inhomogeneities such as bone and airways that significantly affect the dose distribution are treated crudely or ignored. We have developed PEREGRINE, a computer simulation code that combines computed tomography (CT) medical images with a Monte Carlo radiation transport code specifically written for radiation therapy application. PEREGRINE, which uses our evaluated nuclear data bases, extended to the higher energies (~250 MeV) necessary for this application, simulates all major forms of external radiation therapy as well as the effects of internal radioisotope sources. By determining the materials and densities from the patient's CT image, and using the Monte Carlo calculation to explicitly account for the effect of three-dimensional inhomogeneities, PEREGRINE will allow clinicians to predict dose distributions with greater accuracy using a wider range of therapy beam types than any other dose calculation method.

Atomic Physics

We have made significant progress in increasing our understanding of the properties of very highly charged ions and of the behavior of atoms in very strong laser fields.

Highly Charged Ions

The Electron Beam Ion Traps (EBIT and Super EBIT) at LLNL are unique experimental devices for producing, trapping, and extracting ions in extremely high charge states. The Super-EBIT (with beam energy up to 200 keV) allows us to produce and trap any ion, including bare uranium from which all 92 electrons have been removed. For the first time, we accurately measured the removal of the last, most tightly bound electron from very heavy ions. Our measurement for uranium gave a much lower removal rate than the previous experimental value inferred from stripping high-energy uranium beams.

We designed and built a cryogenic particle trap called RETRAP to confine cold, very highly charged ions without any electrons present. It will enable us to experimentally investigate novel states of matter, such as crystals of strongly interacting ions. Our first proof-of-principle experiments raised the maximum charge state of ions confined in such a trap by more than a factor of 6 and showed that slow ions, produced and extracted from EBIT, can be captured in a secondary trap where they are accessible for further cooling.

Results of a 3D PEREGRINE calculation of three 14.1-MeV neutron beams incident on the center of the left lung. The dose distribution is overlaid on the anatomy as defined by a CT-scan of a chest. The brighter colors represent higher dose regions.

Intense Laser–Atom Interactions

High-intensity, ultrashort-pulse lasers allow us to investigate the fundamental process of ionization of atoms and ions in large external electromagnetic fields. Many previous experiments have confirmed the basic theoretical models of the ionization mechanisms appropriate for different laser intensities and pulse lengths. Using LLNL's ultrashort-pulse laser facility, we discovered a new effect: excess production of doubly ionized atoms at laser intensities below the threshold predicted by accepted theories.

To understand the interaction of intense lasers with gaseous media, we must accurately characterize how the energy is transferred from the laser field to the atoms in the gas. Experiments have demonstrated that electrons stripped from atoms by very intense optical laser pulses ultimately have energies in the keV range. Our calculations firmly established that this surprisingly large transfer of energy occurs during a single cycle of the oscillating electromagnetic field of the laser. We have also shown unambiguously that the coherent short wavelength radiation ($\lambda < 10$ nm) and the incoherent x-ray emission that have been observed in experiments are due to collisions of these energetic electrons, either with their parent ions or with other atoms nearby in the gas. We plan to exploit this effect for the production of very short pulses of x rays.

Space Science and Technology

Our expertise and research in space science and technology have led to important new results in astronomy and lunar exploration, as well as to the

The TAISIR and GRATIS instrument package just before launch on a high-altitude balloon. TAISIR provided high-resolution images of thermal emissions on the Earth from space, while GRATIS provided images of astronomical gamma-ray sources.

development of advanced instrumentation for balloon- and satellite-borne platforms.

The MACHO Project

Measurements of the observed motions of stars in the Milky Way suggest that the total mass of the galaxy is 10 to 100 times greater than the estimated total visible mass. Thus, most of the matter in our galaxy must take the form of invisible components called "dark matter." We are continuing our observations to test the hypothesis that the dark matter is made up of massive compact halo objects (MACHOs) such as brown dwarf stars or planets like Jupiter or black-hole remnants of primordial stars.

We are using our charged-coupled-device camera system, the "Super Camera," at the Great Melbourne Telescope in Australia to make photometric measurements of about 8 million stars, looking for gravitational microlensing events as the signature of MACHOs. Since September 1993, when the first unambiguous detection of gravitational microlensing was made, we have observed many more microlensing events than were thought possible. The first events were observed by looking toward a galaxy called the Large Magellanic Cloud (LMC). Subsequently, looking toward the center of our own galaxy, the Milky Way, we detected 45 microlensing events, including one in which the star was amplified by a factor of 17! These discoveries have raised serious doubts about conventional descriptions of our galaxy's structure. The implied mass in stars between us and the center of the galaxy is so high that our observations have generated a variety of new theories about the inner structure of the Milky Way.

The Super Camera is also revolutionizing the study of time-variable stellar phenomena. The sampling of the light curves of variable stars over several years provides details of their variability never seen before, and we are discovering many more variable stars. The Cepheid variables in the LMC, for example, are key in measuring the size of the universe, and their standardization depends upon understanding their behavior as a function of time.

Stellar Opacities

The opacity of light elements plays an important role in the modeling of laser-produced and stellar plasmas. Because unsuccessful attempts to model some observed properties of stars suggested that the opacities were being underestimated, we developed a new computer code that includes improved theoretical models of equation of state, atomic physics, and spectral line broadening. Our calculations show that previous models underestimated the opacity of iron in the 20–120 eV energy range by orders of magnitude. Even with the low abundance of iron in stars, this increases the calculated opacity of stars by factors of 3 to 4 at temperatures near 3×10^5 K. Our predictions have been confirmed by experiments on laser-produced plasmas using LLNL's Nova laser.

The substantial changes in the opacity of light elements have required that many earlier simulations of stellar phenomena be repeated with the new LLNL-produced opacities. This effort has produced several noteworthy successes. For example, the predicted pulsation period of classical Cepheids and RR Lyrae, the nonradial acoustic oscillation spectrum of the Sun, the abundance of lithium in the Hyades cluster stars, and the wind velocity leading to mass loss in classical novae are all in better agreement with observation.

TAISIR and GRATIS

In 1994 we fielded the first high-altitude balloon flight of an instrument package that combined a gamma-ray imager and a remote-sensing experiment prototype system for the TAISIR program. A 10-μm narrow-band infrared imager was piggybacked onto the Gamma Ray Arcminute Telescope Imaging System (GRATIS) operating between 30 and 150 keV. The flight reached an altitude of 40 km and remained aloft for 12 hours, allowing a great deal of data to be taken by both the infrared and gamma-ray instruments.

Although TAISIR is a remote-sensing system intended for future deployment on a satellite platform, high-altitude balloon flights allow tests at a relatively low cost and with a very quick turnaround time. The TAISIR prototype takes advantage of the extremely stable platform developed for the imaging gamma-ray telescope to demonstrate the performance of a diffraction-limited infrared imager. In its first flight, the infrared instrument worked flawlessly, obtaining over 5000 images.

GRATIS also obtained 10 hours of gamma-ray data during the flight, locking onto and tracking three astronomical gamma-ray sources: X-1, an x-ray pulsar; Cyg X-1, a prime black-hole candidate; and Cyg X-3, an unusual x-ray binary system that emits throughout the gamma-ray band. The GRATIS package will fly from the Southern Hemisphere next, where it will image the Galactic center at unprecedented angular resolution.

The Clementine Satellite

The Clementine satellite (the first U.S. spacecraft to the Moon in more than two decades) was launched from Vandenberg Air Force Base on January 25, 1994. Sponsored by the Ballistic Missile Defense Organization, the Clementine experiment was primarily designed to demonstrate lightweight imaging sensors and component technologies for the next generation of Department of Defense spacecrafts, using the Moon, the near-Earth asteroid Geographos, and its own solid-rocket motor as imaging targets. Its secondary mission was to provide scientific data on the mineral content and topology of the lunar surface and on the formation of planets in our solar system. The satellite circled the Moon for over two months beginning February 19. The technology demonstration and lunar-mapping parts of the mission were an unqualified success: the LLNL-developed, on-board cameras returned more than 1.5 million images of the Moon at spatial resolutions never before attained.

Pathfinder and the Development of Solar Rechargeable Aircraft

We are working for the Ballistic Missile Defense Organization to develop unmanned aircraft for protecting our military forces and our allies from attack by theater ballistic missiles. Such aircraft may function as reusable, relocatable, geostationary platforms operating within the atmosphere. Engineers from AeroVironment, Inc. and LLNL have designed and completed flight testing of a solar-powered airplane called Pathfinder. The Pathfinder is a flying testbed for proving key technologies, critical system-integration approaches, and flight-control issues essential to achieving solar-powered flight at high altitude. Fuel-cell technology has been demonstrated to the point that unitized rechargeable fuel cells are possible. Such an energy-storage system weighs less than one-third the weight of the best rechargeable batteries available. The next step would be to build a plane like Pathfinder that has wing dimensions that can accommodate the weight of the rechargeable energy-storage system while enabling it to operate continuously at altitudes of 20 to 25 km.

Operating in the thermal infrared region of the spectrum (8 to 9.5 μm), the long-wave infrared camera was used in the Clementine satellite mission to measure thermal emission from the Moon's surface.

Summary

LLNL scientists conduct physics research ranging from the subatomic to the extra galactic. We design and build devices to investigate the innermost workings of atoms, nuclei, and exotic particles. We also design and build instruments to collect information about the planets and astronomical objects. We use first-principles physics and massively parallel computers to custom-design materials that do not yet exist and to understand the interaction of laser light with matter. Physics research at the Laboratory advances our understanding of the universe and its building blocks, and the development of advanced technologies makes it possible to observe the world around us at an unprecedented scale.

For further information, contact Andrew Hazi (510) 422-4574.